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DDP-116 GENERAL DIGITAL FILTERING

By Jack A. Jones and Ronald J. Graham
Computation Laboratory

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16. ABSTRACT

This report describes the methods for calibrating, selecting filter weights, filtering, and computing filter response functions. These methods are computed on a Statistical Analyzer (STAN) system with a Honeywell DDP-116 Central Processor. The following filter types are computed:

1. All Pass
2. Low Pass
3. High Pass
4. Band Pass
5. Band Rejection
6. Derivative

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LIST OF ILLUSTRATIONS

NOMENCLATURE

ADC	Analog-to-digital converter
N	Integer associated with number of weights
$2N + 1$	Number of weights used to filter
f	Frequency variable, usually hertz (Hz)
f_c	Cutoff frequency
f_t	Termination frequency
f_s	Sampling frequency, number of samples per second
$\Delta t = \frac{1}{f_s}$	Time between samples
$G(f)$	Gain variable associated with frequencies in describing a filter
Δf	Difference between termination frequency and cutoff frequency
$h(n)$, h_n, H_n	Filter weights
$h_L(n)$	Subscript refers to weight type; the example is a low-pass filter
$h_A(n)$	All-pass filter weights
$h_B(n)$	Band-pass filter weights
$h_H(n)$	High-pass filter weights
$h_{BR}(n)$	Band-rejection filter weights
d_k	Digital data
D_n	Derivative weights

NOMENCLATURE (Concluded)

HR	Real component of response
PR	Imaginary component of response
R, R^1	Normalized frequency variable; that is, f/f_s
F, F^1	Frequency variable for plotting in cycles per second (cps)

TECHNICAL MEMORANDUM X-64697

DDP-116 GENERAL DIGITAL FILTERING

INTRODUCTION

The purpose of this program is to offer a general purpose digital filtering capability on the Statistical Analyzer (STAN) system (Appendix A). The filtering methods used in this program are those methods developed by Martin-Graham, as discussed in Reference 1. The following filtering capabilities are available.

1. All Pass

2. Low Pass

3. High Pass

4. Band Pass

5. Band Rejection

6. Derivative

INPUT

The program possesses capabilities to filter either raw, unconverted digital data or engineering unit data. Input tapes can assume any of the following forms:

1. Astrodata analog-to-digital converter (ADC)

2. Scientific Data Systems

3. MSFC format

4. S&E-COMP-RRF binary tape (same as item 3 except header record is missing)

5. Cycle counter

The Astrodata ADC, the cycle counter, and the Scientific Data Systems produce raw data that can be converted to engineering units using either sine or step calibrations. Descriptions of the above tape formats may be obtained from the authors.

CALIBRATION

The maximum (C_2) and minimum (C_1) calibration count levels are computed for the sine calibration by

$$C_2 = 1.414 \sqrt{\frac{1}{N} \sum_{i=1}^{N} X_i^2 - \overline{C}^2} \quad , \tag{1}$$

$$C_1 = -C_2 \quad , \tag{2}$$

and

$$\overline{C} = \frac{1}{N} \sum_{i=1}^{N} X_i \quad , \tag{3}$$

where

X_i = the data count in a calibration file ,

$i = 1, 2, \ldots, N$,

and

N = the number of data points in a calibration file .

The slope is computed by

$$S = \frac{E_2 - E_1}{C_2 - C_1} \tag{4a}$$

where E_2 and E_1 are maximum and minimum engineering units. When a sine wave is used for calibration,

$$S = \frac{E_2 - E_1}{2C_2} \quad , \tag{4b}$$

and the offset is computed by

$$0 = E_2 - S(C_2 + \overline{C}) \quad . \tag{5}$$

The raw data points (X_i) are converted to engineering units (d_i) by

$$d_i = S \cdot X_i + 0 \quad . \tag{6}$$

The maximum (C_2) and minimum (C_1) calibration count levels are computed for the step calibration. First the maximum count level (C_2) is considered. The mean $(\overline{C})$ and standard deviation (C_s) count level for the maximum calibration level are computed by

$$\overline{C} = \frac{1}{N} \sum_{i=1}^{N} C_i \qquad i = 1, 2, \ldots, N, N \approx 200 \quad , \tag{7}$$

$$C_s = \frac{1}{N} \sqrt{\sum_{i=1}^{N} C_i^2} \qquad i = 1, 2, \ldots, N, N \approx 200 \quad , \tag{8}$$

$$C_{max} = \bar{C} + C_s \quad , \tag{9}$$

and

$$C_{min} = \bar{C} - C_s \quad . \tag{10}$$

All C_i are interrogated for the value ($C_{max} \geq C_i \geq C_{min}$), and any C_i outside these limits is rejected. All data within these limits are accepted and equations (7) through (10) are repeated until $C_s \leq 1$. When this condition is met, the minimum calibration level C_1 is computed identically to C_2. After C_2 and C_1 are computed, equations (4) through (6) are used to compute d_i.

FILTERING

Filter Weights

Generally the number of filter weights $(2N + 1)$ is chosen such that a given amplitude error is maintained over the intervals $0 \leq f \leq f_c$ and $f_t \leq f \leq f_s/2$, where f is the frequency variable, f_c is the cutoff frequency, f_t is the termination frequency, and f_s is the sampling frequency (Fig. 1).

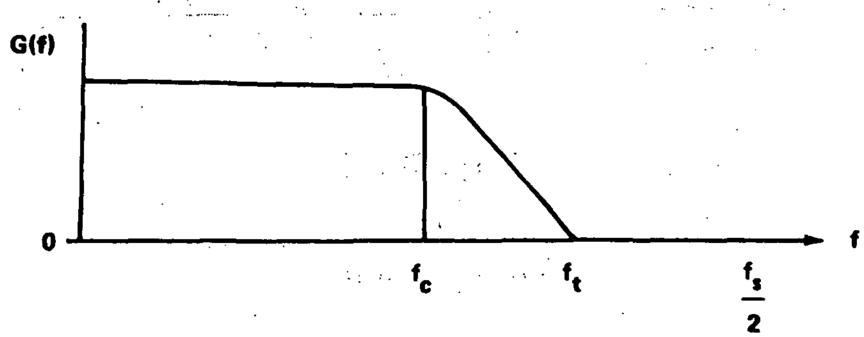


Figure 1. Filter definition.

Error Analysis. The error is defined as the difference between the ideal filter curve and the actual response curve in the intervals $0 \le f \le f_c$ and $f \ge f_t$. The errors discussed refer to the maximum errors and occur at no more than two points. The average error and the expected error are much less than the maximum errors discussed. The percent of maximum error is defined in terms of the following parameters:

N — where $2N + 1$ is the number of filter weights.

Δt — interval between consecutive data points (independent variable).

Δf — filter termination frequency, f_t, minus filter cutoff frequency, f_c.

Figure 2 illustrates these results. The table inset in Figure 2 is used to compute N, the number of weights being $2N + 1$, as follows:

1. The percent of maximum amplitude error as a function of $N\Delta t\Delta f$ is shown in Figure 2. This curve will be used by the analyst to determine the optimum selection of N and Δf.

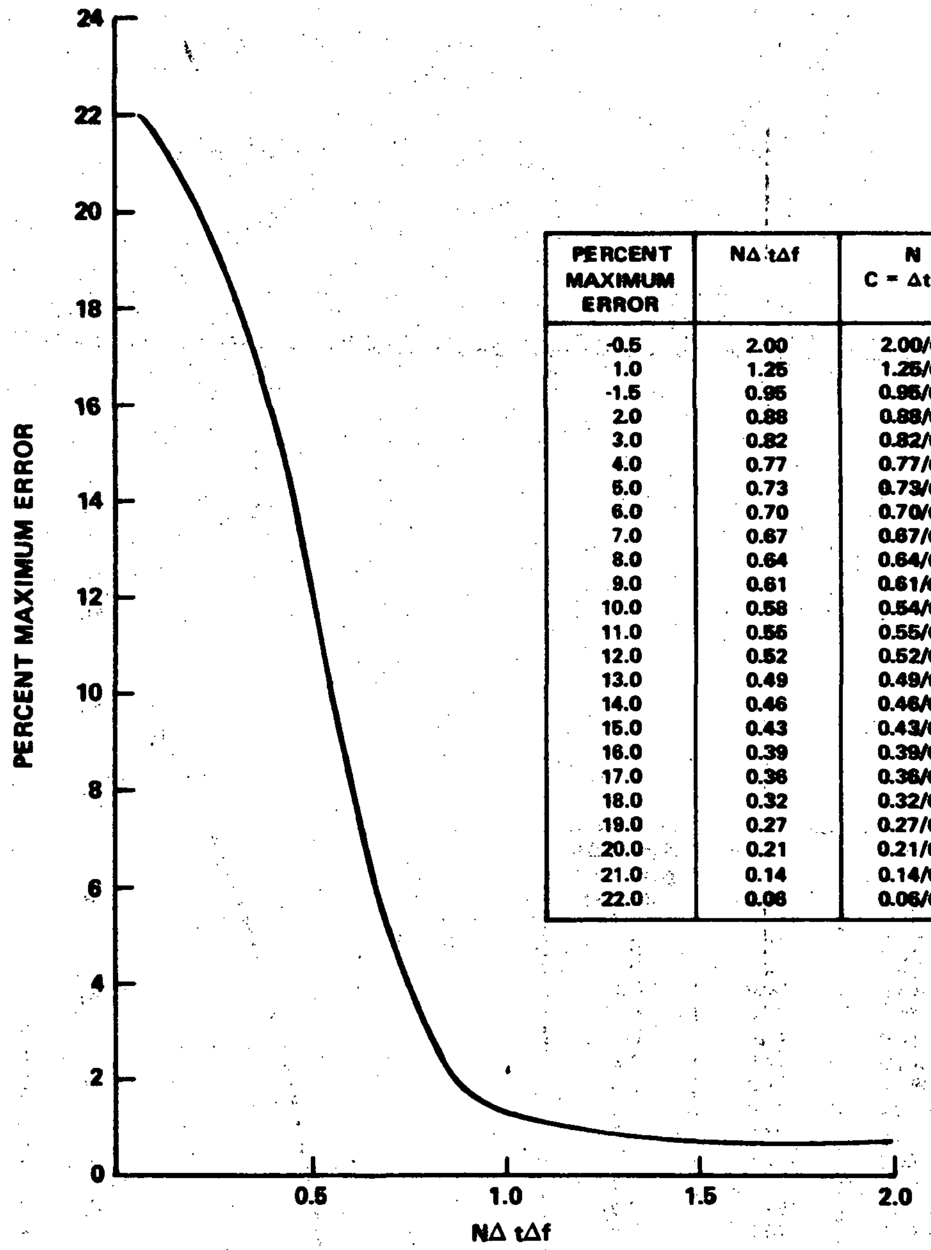
2. Normally Δt is a fixed parameter; i.e., the sampling rate should be at least four times the bandwidth of the unfiltered function. Using 40 000 samples per second as the maximum sampling rate, the following values will be realized:

$$2.5 \times 10^{-5} \le \Delta t \le 1 \quad ,$$

$$f_c = 10\ 000 \text{ Hz} \quad ,$$

and

$$f_t = 20\ 000 \text{ Hz} \quad .$$



PERCENT MAXIMUM ERROR	NΔ tΔf	N C = Δt Δf
-0.5	2.00	2.00/C
1.0	1.25	1.25/C
-1.5	0.95	0.95/C
2.0	0.88	0.88/C
3.0	0.82	0.82/C
4.0	0.77	0.77/C
5.0	0.73	0.73/C
6.0	0.70	0.70/C
7.0	0.67	0.67/C
8.0	0.64	0.64/C
9.0	0.61	0.61/C
10.0	0.58	0.54/C
11.0	0.55	0.55/C
12.0	0.52	0.52/C
13.0	0.49	0.49/C
14.0	0.46	0.46/C
15.0	0.43	0.43/C
16.0	0.39	0.39/C
17.0	0.36	0.36/C
18.0	0.32	0.32/C
19.0	0.27	0.27/C
20.0	0.21	0.21/C
21.0	0.14	0.14/C
22.0	0.06	0.06/C

Figure 2. Error curve.

3. Δf is chosen such that all unwanted data are rejected.

4. N is chosen such that an acceptable error is maintained. The operator must judiciously select N to minimize computing time and still maintain an acceptable error.

5. The optimum error value for most applications will be 1.5 percent for which

$$N = \frac{0.95}{\Delta t \, \Delta f} \text{ (round } N \text{ up to the nearest integer)} \quad , \tag{11}$$

where

$$\Delta t = \frac{1}{\text{sampling rate}} \quad ,$$

$$\Delta f = f_t - f_c \quad ,$$

$$f_t = \text{termination frequency} \quad ,$$

and

$$f_c = \text{cutoff frequency} \quad .$$

All-Pass Filter Weights

All-pass filter weights $h(n)$ yield

$$h(n) = \begin{cases} 0; \; -N \leq n \leq -1 \\ 1; \; n = 0 \\ 0; \; 1 \leq n \leq N \end{cases} \quad . \tag{12}$$

Low-Pass Filter Weights

A test for a singular point occurrence is performed:

$$n = \frac{0.5}{(\Delta t)\,(\Delta f)} \quad . \tag{13}$$

If n is an integer, then

$$h(n\Delta t) = \Delta t \left[\frac{\Delta f}{2} \cos\left(\frac{\pi}{f_t/f_c - 1} \right) \right] . \tag{14}$$

For all nonintegers,

$$h_L(n) = \frac{1}{2\pi n} \left[\frac{\sin(2\pi f_t n\Delta t) + \sin(2\pi f_c n\Delta t)}{1 - 4(\Delta f)^2 (n\Delta t)^2} \right] . \tag{15}$$

There are $2N + 1$ weights $(h_n, h_{n+1}, \ldots, h_0, \ldots, h_{n-1})$. Equation (15) is evaluated for all values of $n = 1, 2, 3, \ldots, N$, noting that $h(n) = h(-n)$. This yields $2N$ weights and $h(0) = \Delta t\,(f_c + f_t)$, thus producing the central value of the $2N + 1$ values.

The set of weights $h_L(n)$ constitutes the weights for a low-pass filter with the following characteristics:

$$G(f) = \begin{cases} 1; \; 0 \le f \le f_c \\ \dfrac{1}{2}\left\{ \cos\left[\dfrac{(f - f_c)}{\Delta f} \right] + 1 \right\}; \; f_c \le f \le f_t \\ 0; \; f_t \le f \le (f_s - f_t) \end{cases} . \tag{16}$$

High-Pass Filter Weights

The following equations illustrate high-pass filter weights:

$$\left.\begin{aligned} h_H(0) &= 1 - h_L(0) \text{ for } n = 0 \\ h_H(n) &= -h_L(n) \text{ for } n \ne 0 \end{aligned}\right\} . \tag{17}$$

When combining two sets of weights by equation (17), an equal number of weights must be considered by both filters.

Band-Pass Filter Weights

The band-pass filter weights $h_B(n)$ are defined as the corresponding differences between two low-pass weight sets; that is,

$$h_B(n) = h_L(n) - h_L^{1}(n) \quad . \tag{18}$$

This has the same effect as geometrically subtracting the filter gain (Fig. 3).

Band-Rejection Filter Weights

The band-rejection filter weights $h_{BR}(n)$ are computed by negating all the band-pass weights except the central weight, which is subtracted from unity:

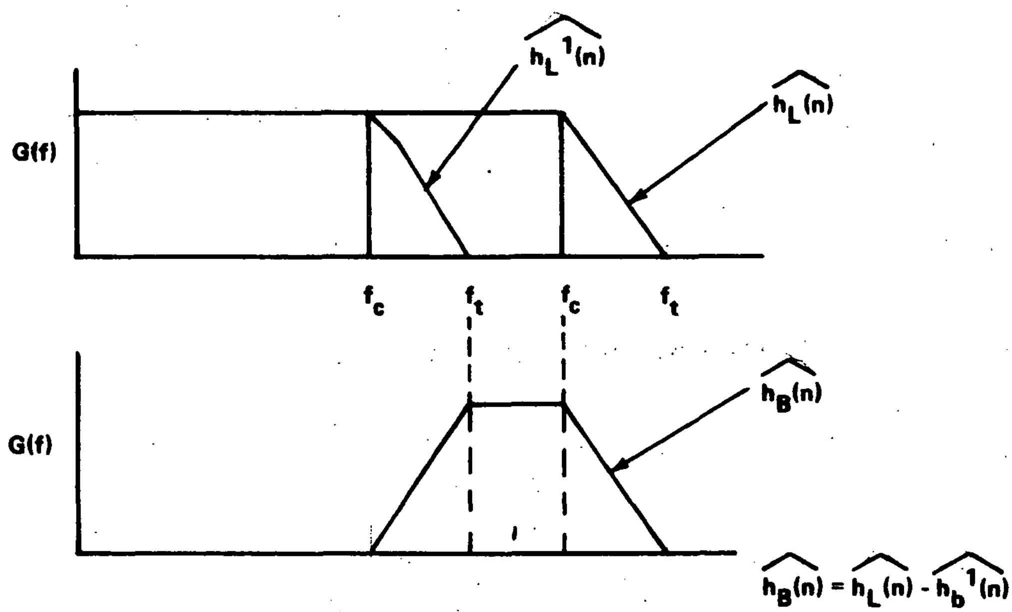


Figure 3. Band-pass filter.

$$h_{BR}(n) = h_A(n) - h_B(n) \quad , \tag{19a}$$

or

$$h_{BR}(n) = -h_B(n) \quad , \tag{19b}$$

except

$$h_{BR}(0) = 1 - h_B(0) \quad .$$

APPLICATION OF WEIGHTS

After the filter type is selected and the weights are computed, they are normalized for the low-pass filter only:

$$H_L n = \frac{h_L(n)}{\sum_{n=-N}^{N} h_L(n)} \quad . \tag{20}$$

Next, the weights $H_K(n)$ are applied to the linearized data, with $K = A, B, L, BR$ designating the filter type,

$$d_{N+1}{}^{1} = \sum_{n=-N}^{N} H_K(n)\, d_{[(N+n)+1]} \quad , \tag{21}$$

where

$$d_{(N+n+1)} = d_1, d_2, \ldots, d_{(n+1)}, \ldots, d_{(2N+1)} \quad .$$

The smoothing process is initiated by assuming data values to the left equal to those on the right. For example, if raw data starts at d_s, then $d_{s+K} = d_{s-K}$, where $K = 1, \ldots, N$.

A similar procedure is used for the end points d_e; $d_{e-K} = d_{e+K}$, $K = 1, 2, \ldots, N$.

DERIVATIVE WEIGHTS

If derivative weights are desired the following procedure applies. For the central weight,

$$D(0) = 0 \tag{22}$$

and, with the exception of a possible singular weight, all other weights are

$$D_n = h_n \left\{ \frac{[1 - 12(\Delta f \Delta tn)^2] - [f_t \Delta t \cos(2\pi f_t \Delta tn) + f_c \Delta t \cos(2\pi f_c \Delta tn)]}{n\Delta t[1 - 4(\Delta f \Delta tn)^2]} \right\} , \tag{23}$$

where

$$n = 1, 2, \ldots, N \quad .$$

The negative weights become

$$D_{-n} = -D_n \quad . \tag{24}$$

The singular derivative weight is computed when

$$n = \frac{0.5}{(\Delta t)\,(\Delta f)} \quad . \tag{25}$$

Then,

$$D_n = -0.5\Delta t \left\{ \pi \left[f_t^2 \sin\left(\frac{\pi f_t}{\Delta f}\right) + f_c^2 \sin\left(\frac{\pi f_c}{\Delta f}\right) \right] + 3\Delta f \left[f_t \cos\left(\frac{\pi f_t}{\Delta f}\right) + f_c \cos\left(\frac{\pi f_c}{\Delta f}\right) \right] \right\} . \tag{26}$$

After the derivative weights are computed, the filter configuration is selected:

1. Low pass; $D(n)$.

2. All-pass derivative weights;

$$D_A(n) = \left| \begin{array}{l} 0;\ n = 0 \\ \dfrac{f_s(-1)^{n+1}}{n};\ n \neq 0 \end{array} \right. \quad : \tag{27}$$

3. Band pass;

$$D_B(n) = D_L(n) - D_L{}^1(n) \quad . \tag{28}$$

4. Band rejection;

$$D_{BR}(n) = D_A(n) - D_B(n) \quad . \tag{29}$$

5. High pass;

$$D_N(n) = D_A(n) - D_L(n) \quad . \tag{30}$$

TRANSFER FUNCTIONS

Options are available to plot the selected filter transfer functions or response curves. The phase and gain are computed and plotted as a function of frequency:

$$HR = \sum_{i=1}^{2N+1} h_i \cos\left\{[i - (N + 1)]\ 2\pi R^1\right\} \tag{31}$$

and

$$PR = \sum_{i=1}^{2N+1} h_i \sin\left\{[i - (N + 1)]\ 2\pi R^1\right\} \quad . \tag{32}$$

The gain $G(f)$ is computed;

$$G(f) = \sqrt{(1 + R)^2 + (PR)^2} \quad . \tag{33}$$

The phase response ϕ is computed;

$$\phi = \tan^{-1}(PR/HR) \quad . \tag{34}$$

The gain and phase are computed at the discrete points;

$$R = 0,\ 0.01,\ 0.02,\ \ldots\ ,\ 0.51 \tag{35}$$

and are plotted at the discrete frequency points

$$F = 0\ f_s,\ 0.01\ f_s,\ 0.02\ f_s,\ \ldots\ ,\ 0.51\ f_s \quad . \tag{36}$$

The abscissa is scaled by computing R^1 and F^1;

$$R^1 = RK + \Delta tC \quad , \tag{37}$$

and

$$F^1 = FK + C \quad , \quad F = n(0.01) \text{ and } n = 0, 1, \ldots, 51 \quad , \tag{38}$$

where K is a multiplication factor and C is a constant to shift the response curve from zero frequency.

For example, assume that $f_s = 100$, then the response curve will be plotted at the discrete points 0, 1, 2, ... , 51; however, if better resolution is desired, equations (37) and (38) apply. Assuming the area of interest is over the interval

$$5 \leq f \leq 10 \quad ,$$

let

$$C = 5$$

and

$$K = 1 \quad .$$

Then,

$$F^1 = (0 + 5), (0.1 + 5), (0.2 + 5), \ldots, (5.1 + 5) \quad .$$

The ordinate for the phase is plotted over the interval $-180° \leq \phi \leq 180°$.

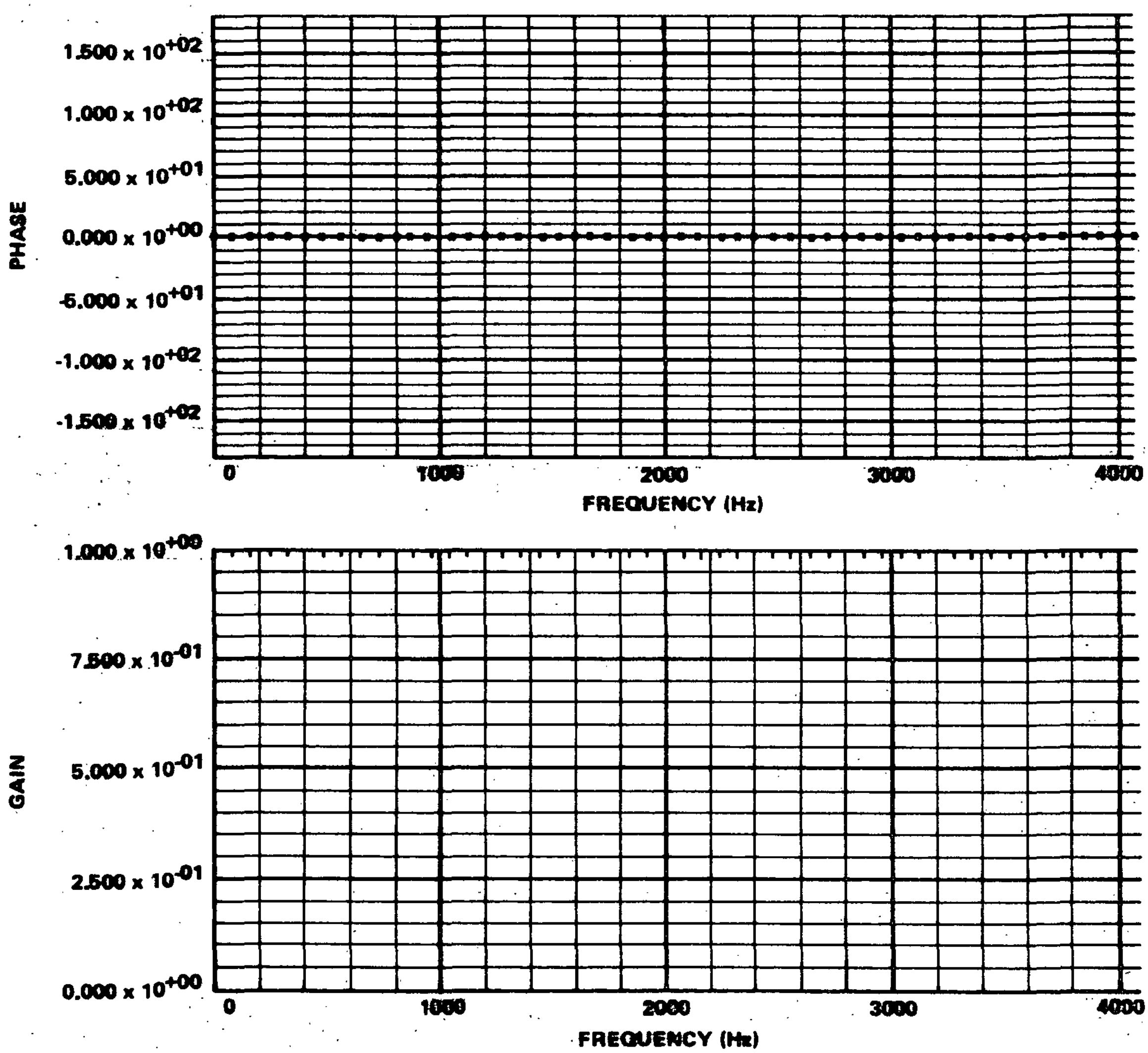
DATA RESULTS

The plots on the following pages illustrate the various filter configurations as applied to a square wave that is a composite of odd harmonics extending to the upper frequencies limited by the Nyquist frequency.

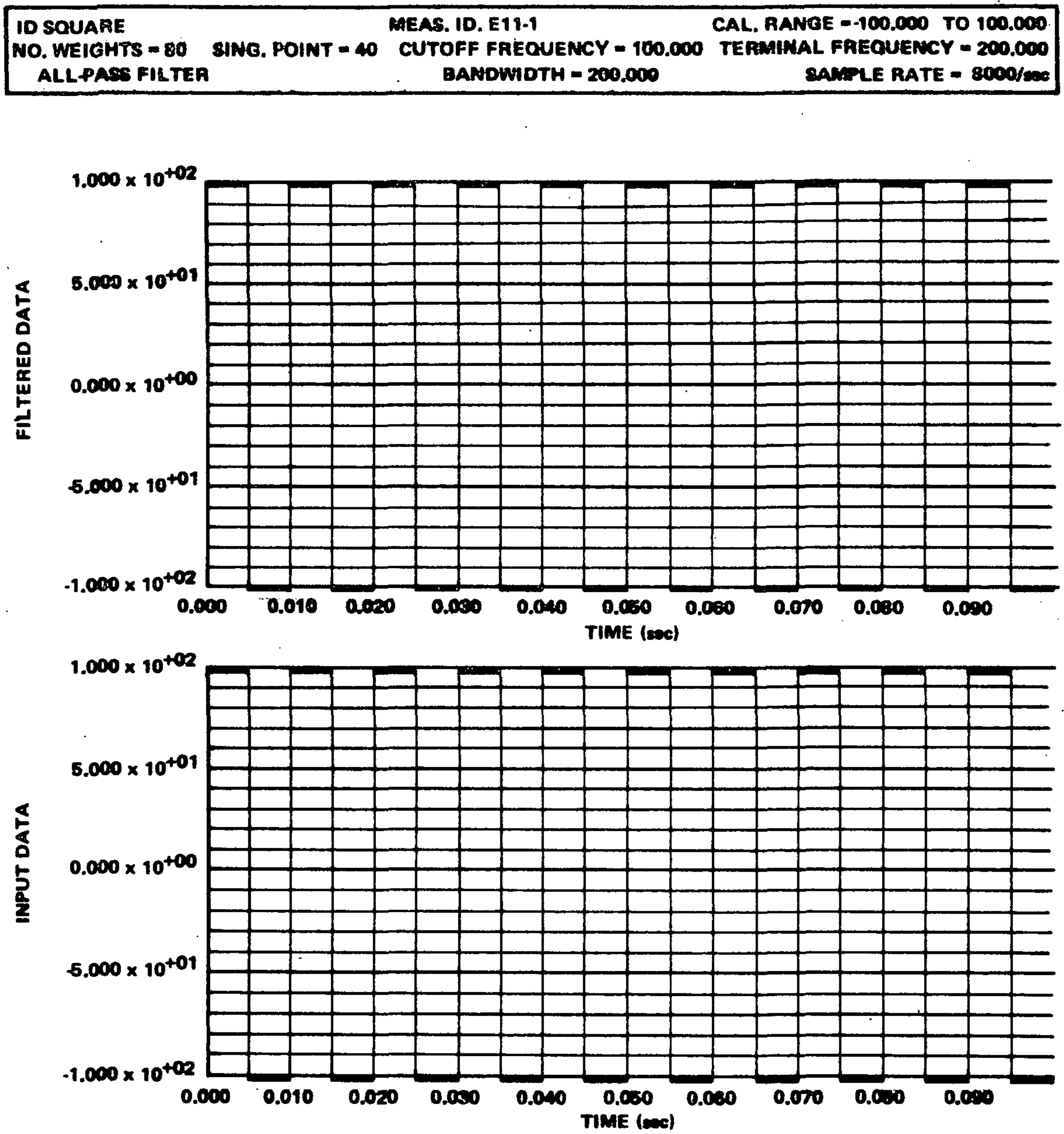
CONCLUSION

The DDP-116 General Digital Filtering program is a general purpose filter program designed to run under the STAN operating system. The program is designed to interface with all elements of the Data Reduction Branch to provide general purpose filtering services.

NO. WEIGHTS = 80 SING. POINT = 40 CUTOFF FREQUENCY = 100.000 TERMINAL FREQUENCY = 200.000
ALL-PASS FILTER BANDWIDTH = 200.000 SAMPLE RATE = 8000/sec
RESPONSE CURVES FACTOR = 8000.000 CONSTANT = 0.000

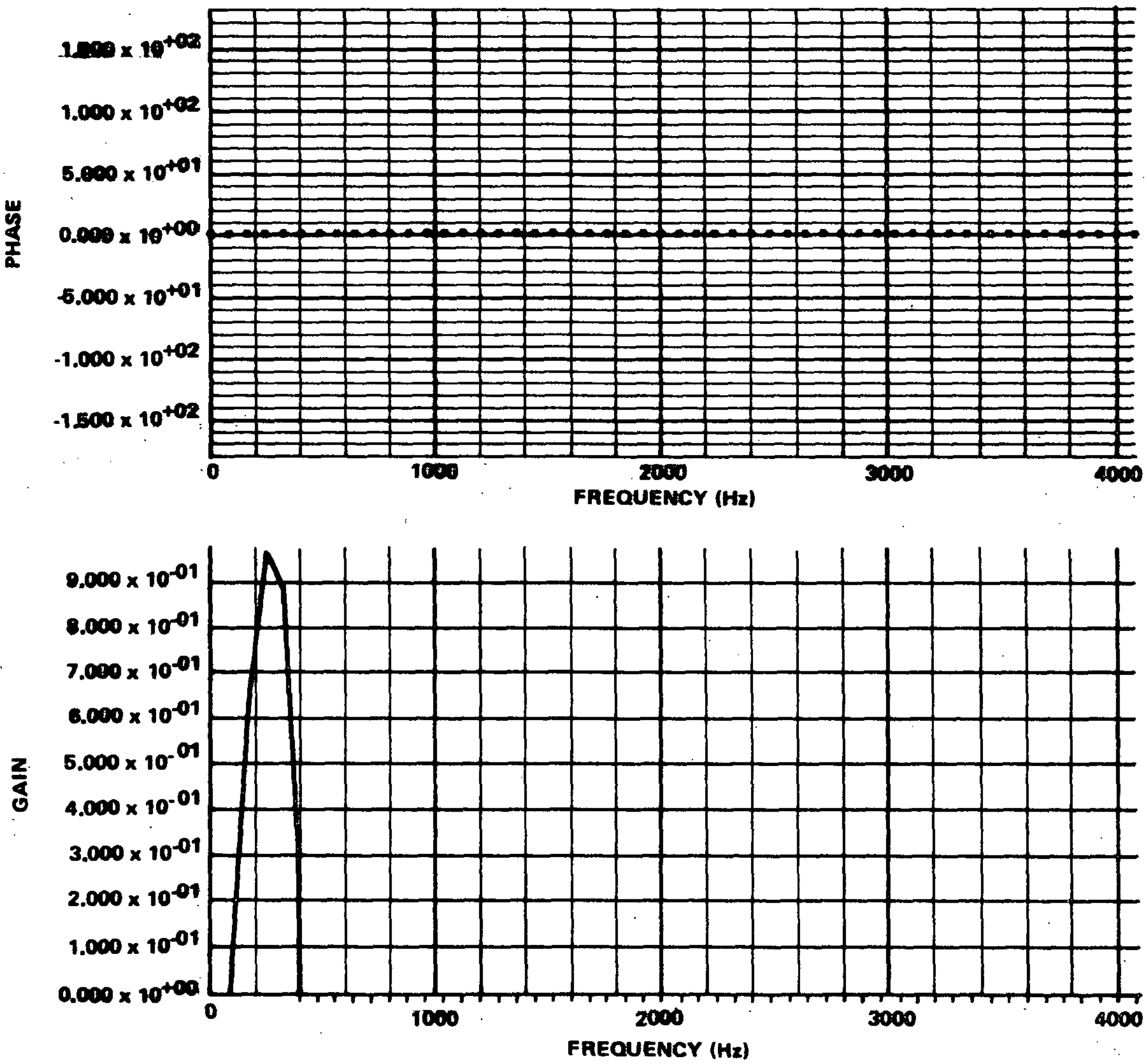


Response Curve for an All-Pass Filter

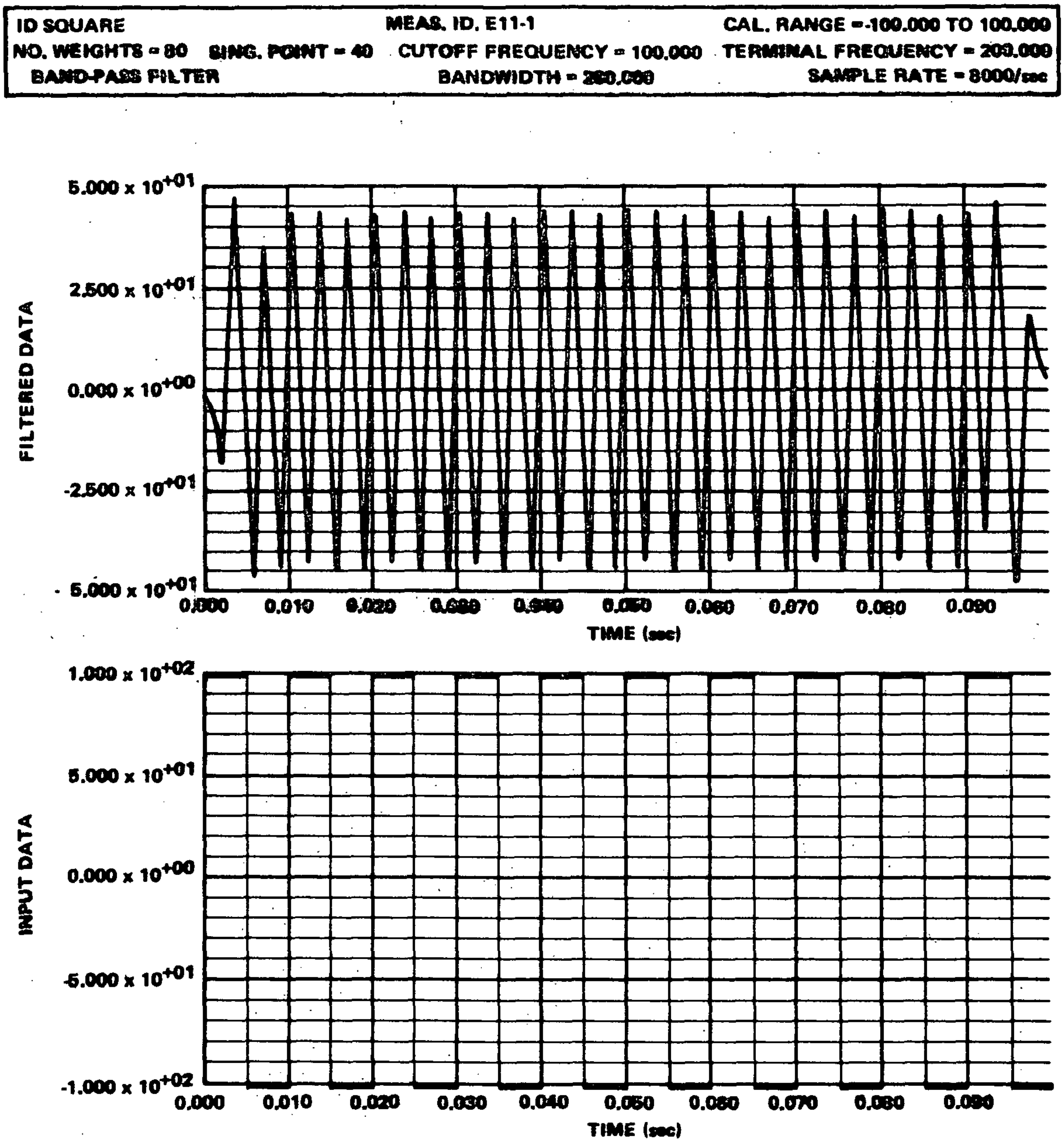


All-Pass Filter Output and Input

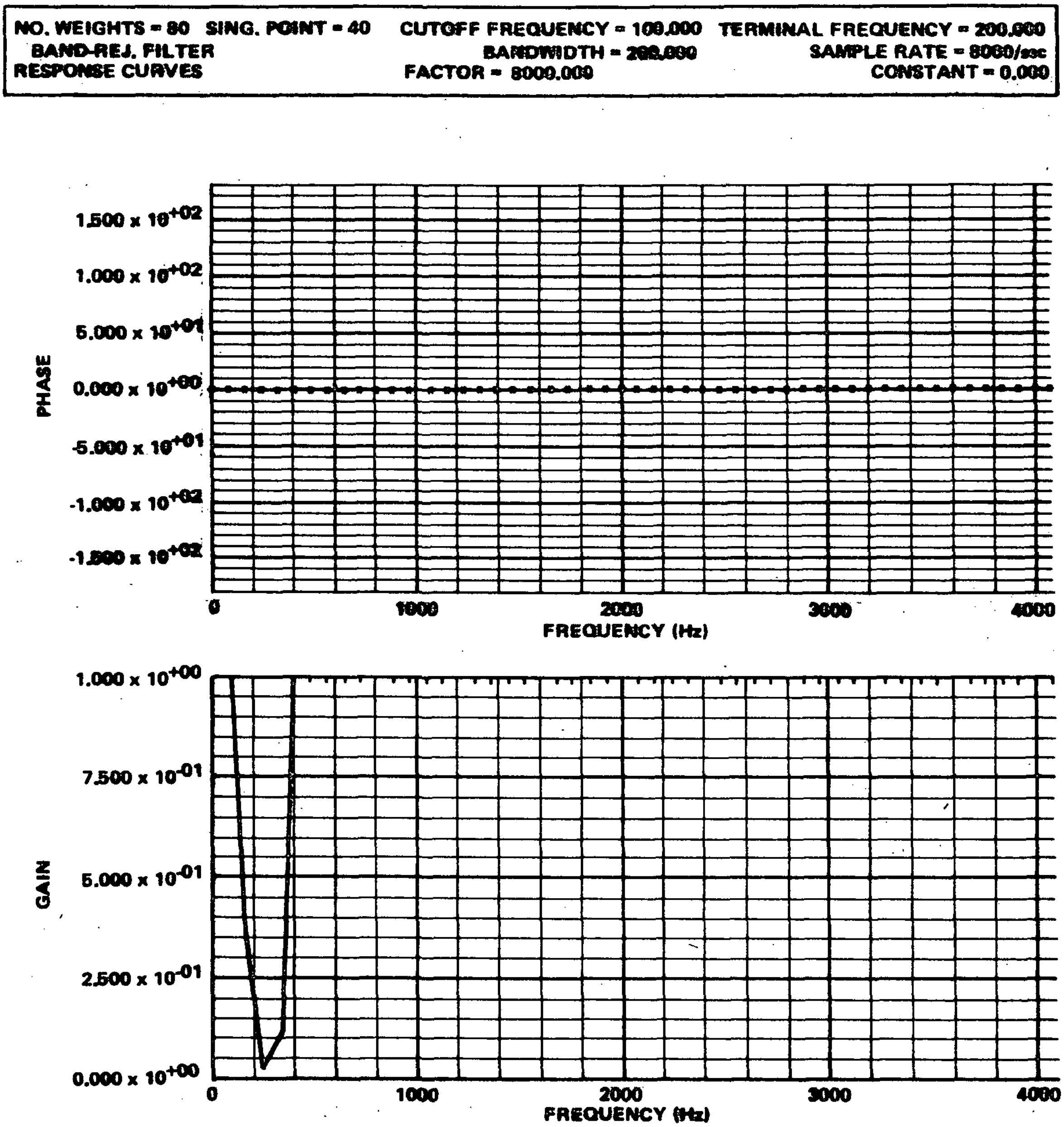
NO. WEIGHTS = 80   SING. POINT = 40   CUTOFF FREQUENCY = 100.000   TERMINAL FREQUENCY = 200.000
BAND-PASS FILTER   BANDWIDTH = 200.000   SAMPLE RATE = 8000/sec
RESPONSE CURVES   FACTOR = 8000.000   CONSTANT = 0.000



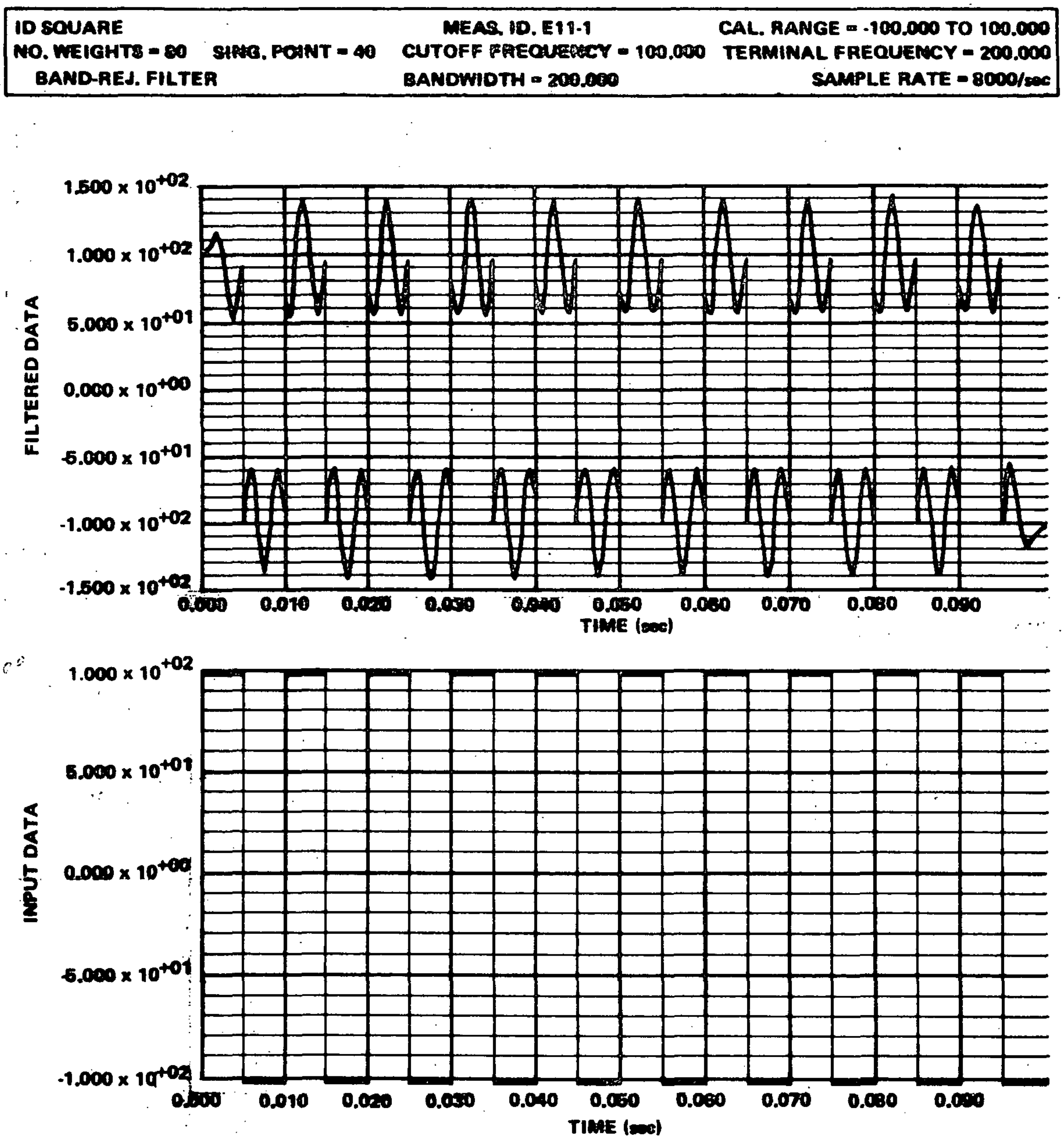
Response Curve for a Band-Pass Filter



Band-Pass Filter Output and Input

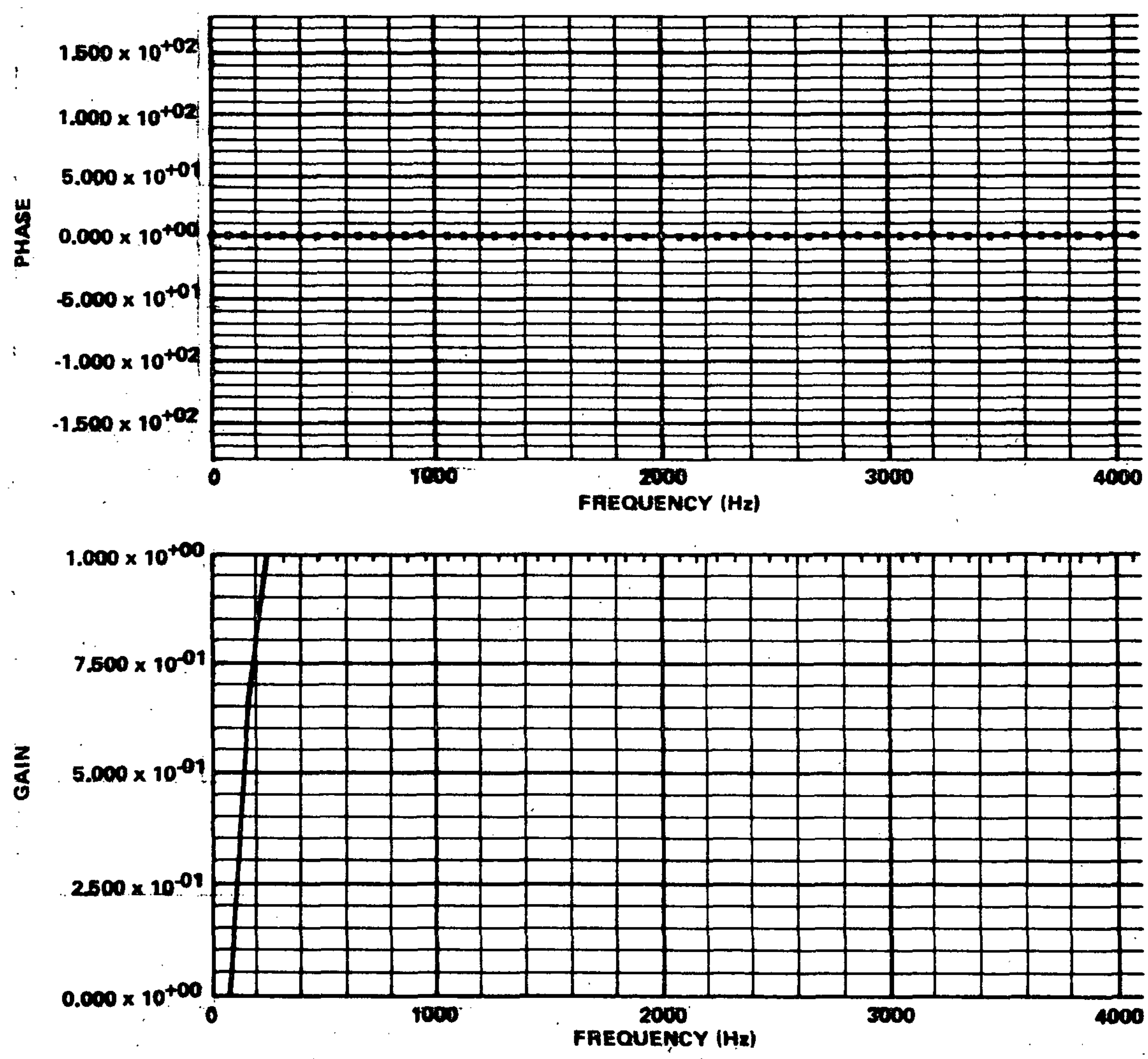


Response Curve for a Band-Rejection Filter

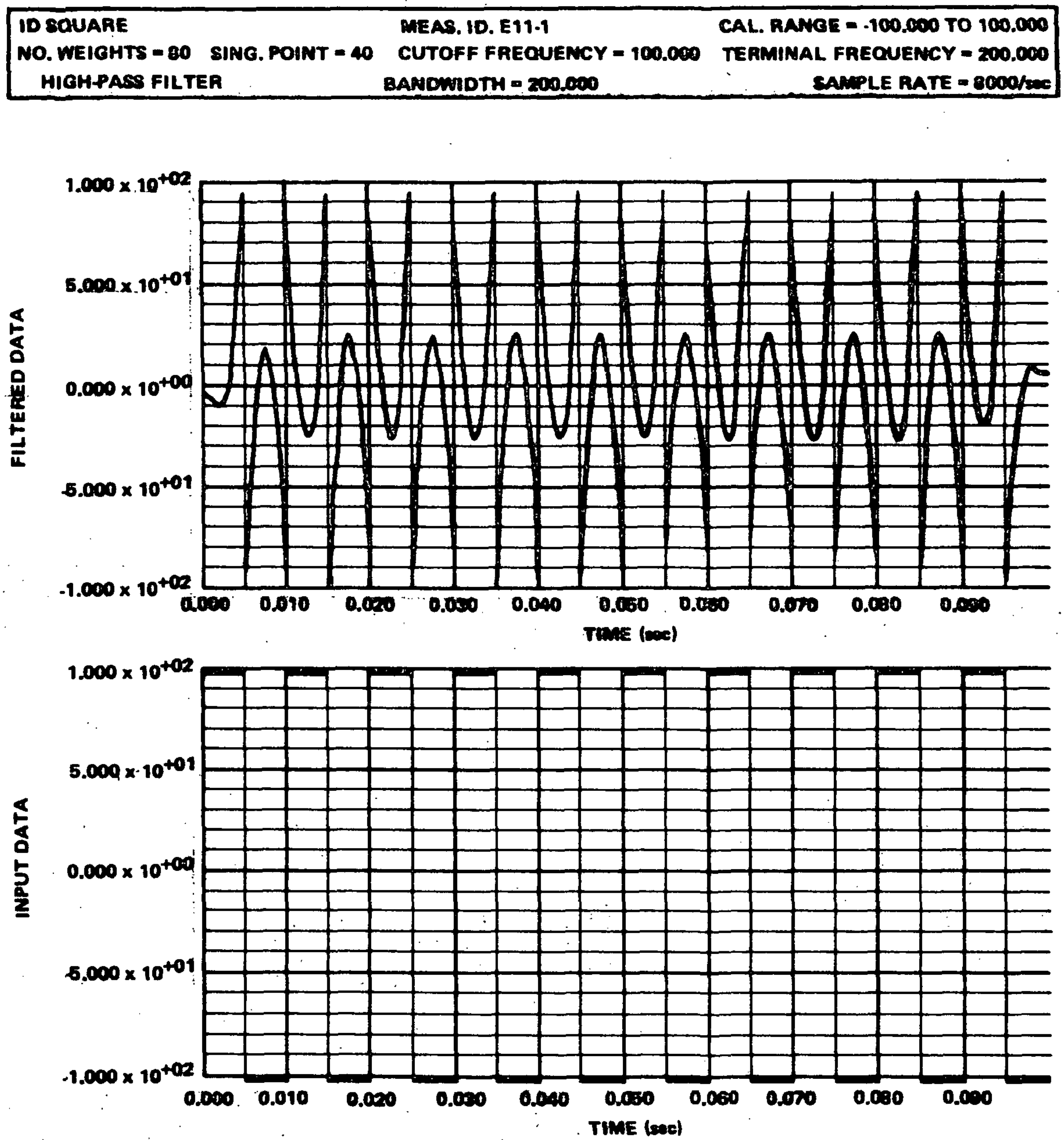


Band-Rejection Filter Input and Output

NO. WEIGHTS = 80 SING. POINT = 40 CUTOFF FREQUENCY = 100.000 TERMINAL FREQUENCY = 200.000
HIGH-PASS FILTER BANDWIDTH = 200.000 SAMPLE RATE = 8000/sec
RESPONSE CURVES FACTOR = 8000.000 CONSTANT = 0.000

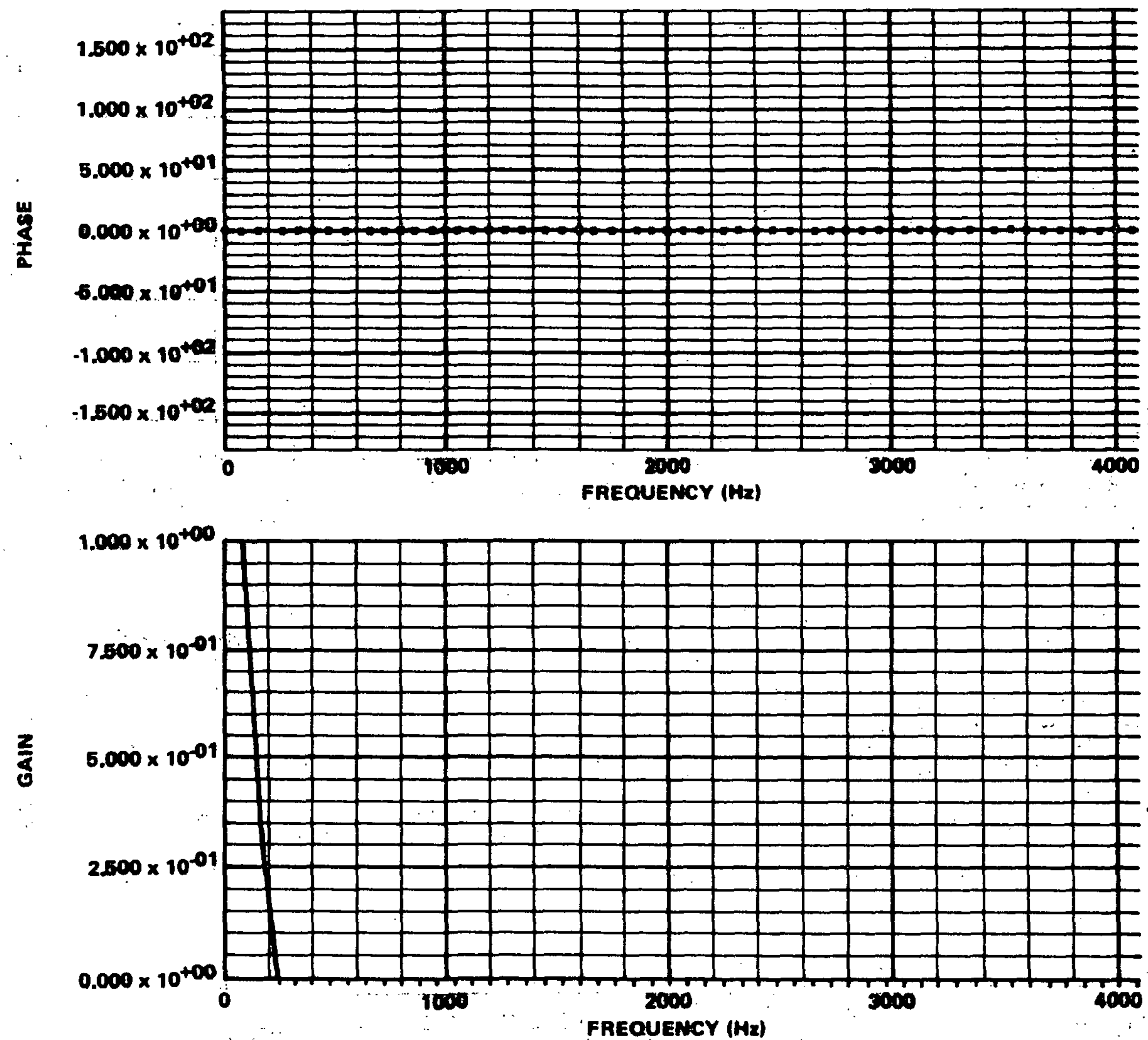


Response Curve for a High-Pass Filter



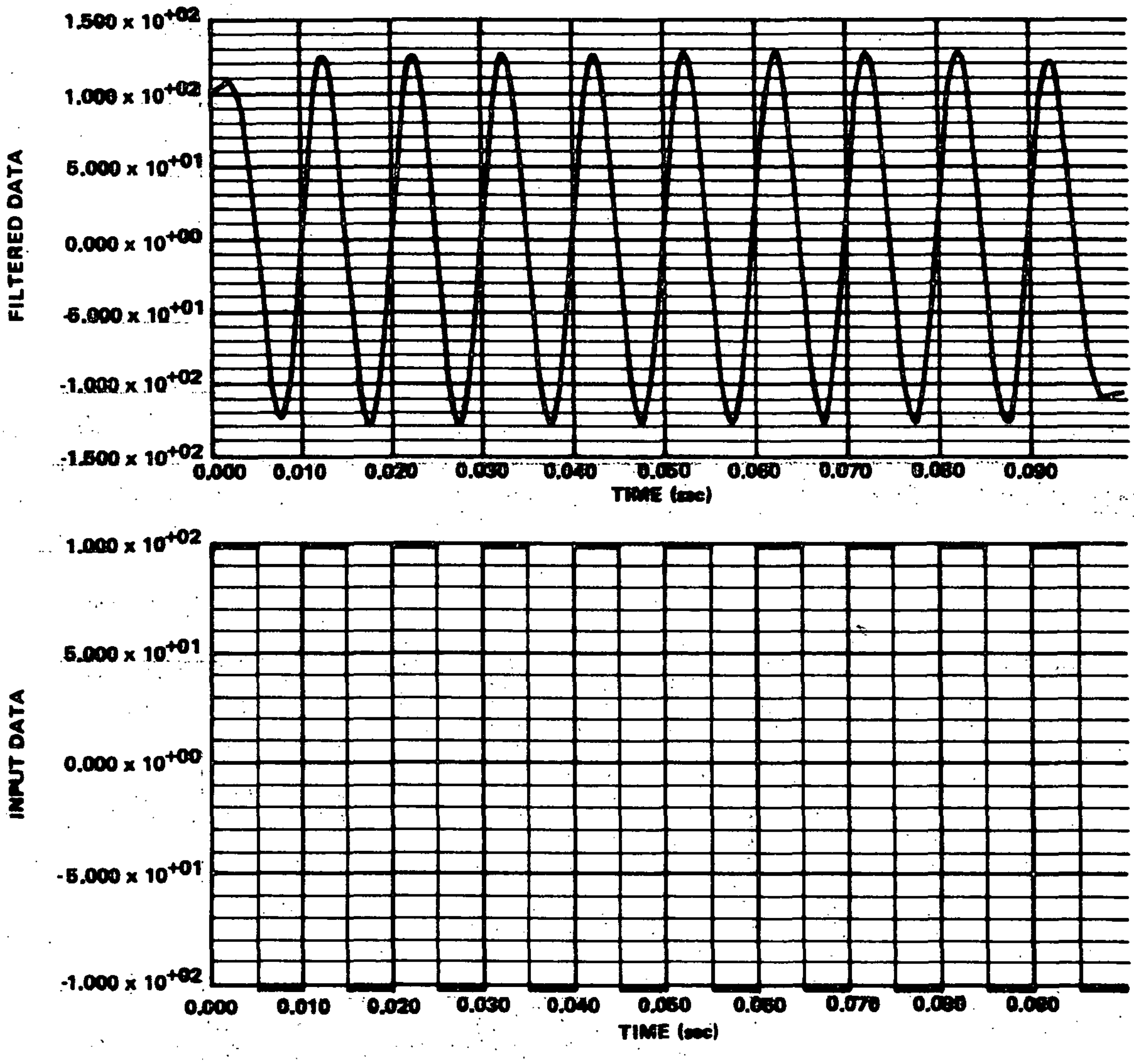
High-Pass Filter Input and Output

NO. WEIGHTS = 80	SING. POINT = 40	CUTOFF FREQUENCY = 100.000	TERMINAL FREQUENCY = 200.000
LOW-PASS FILTER		BANDWIDTH = 200.000	SAMPLE RATE = 8000/sec
RESPONSE CURVES		FACTOR = 8000.000	CONSTANT = 0.000



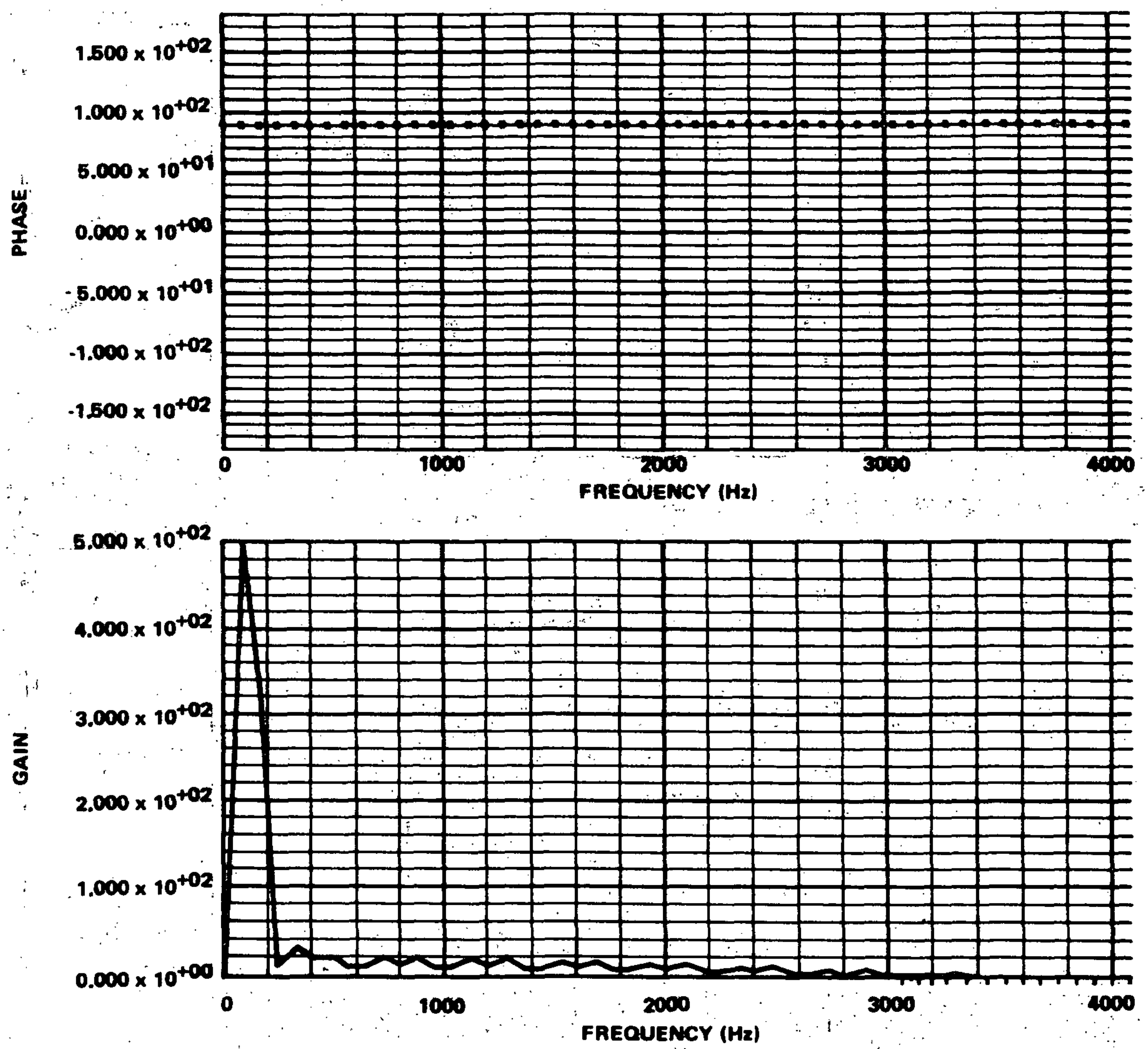
Response Curve for a Low-Pass Filter

ID SQUARE	MEAS. ID. E11-1	CAL. RANGE = -100.000 TO 100.000
NO. WEIGHTS = 80 SING. POINT = 40	CUTOFF FREQUENCY = 100.000	TERMINAL FREQUENCY = 200.000
LOW-PASS FILTER	BANDWIDTH = 200.000	SAMPLE RATE = 8000/sec



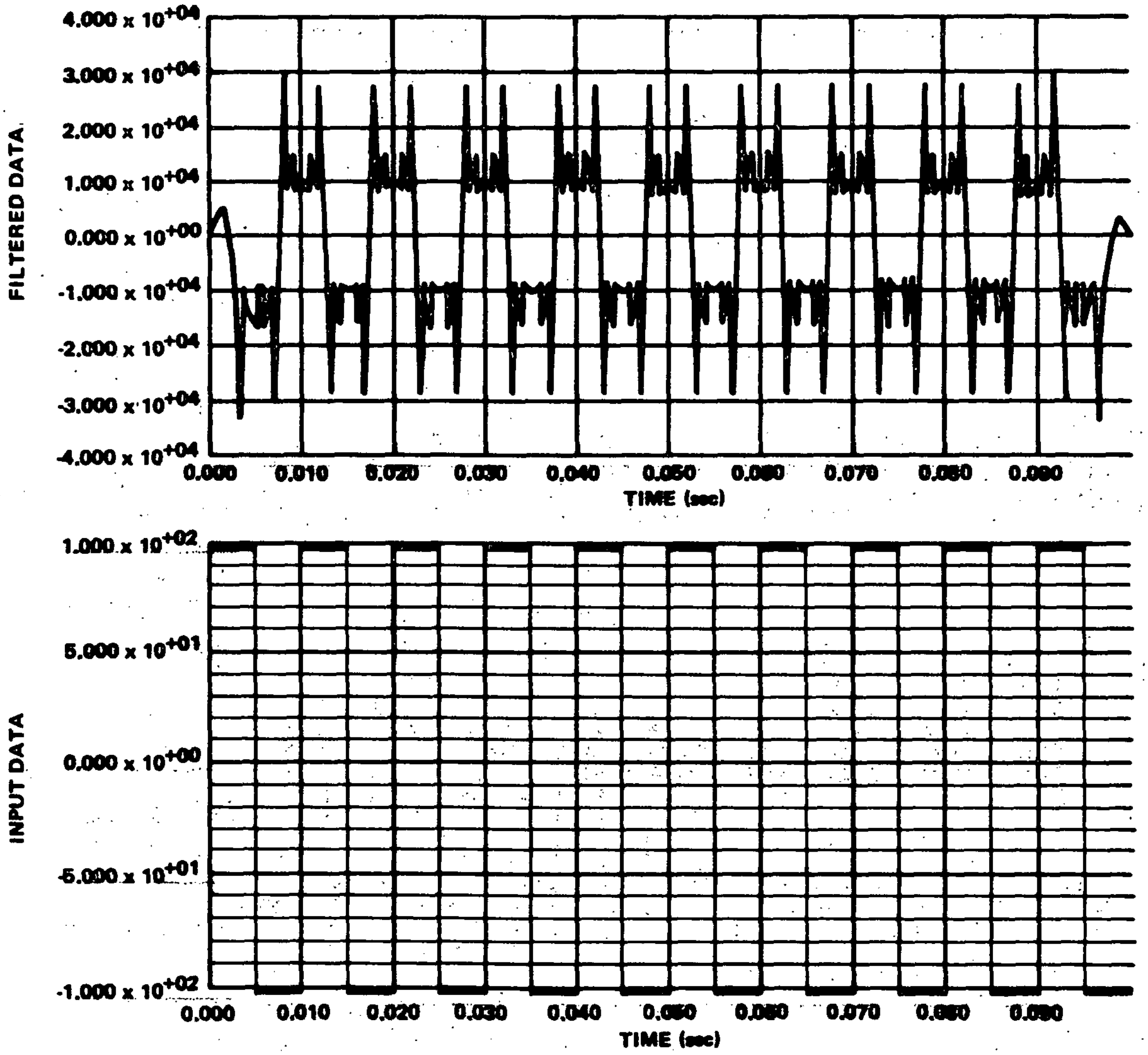
Low-Pass Filter Input and Output

NO. WEIGHTS = 80 SING. POINT = 40 CUTOFF FREQUENCY = 100.000 TERMINAL FREQUENCY = 200.000
LOW-PASS FILTER DERIVATIVE BANDWIDTH = 200.000 SAMPLE RATE = 8000/sec
RESPONSE CURVES FACTOR = 8000.000 CONSTANT = 0.000



Response Curve for a Low-Pass Filter Derivative

ID SQUARE		MEAS. ID. E11-1	CAL. RANGE = -100.000 TO 100.000
NO. WEIGHTS = 80	SING. POINT = 40	CUTOFF FREQUENCY = 100.000	TERMINAL FREQUENCY = 200.000
LOW-PASS FILTER	DERIVATIVE	BANDWIDTH = 200.000	SAMPLE RATE = 8000/sec



Low-Pass Filter Derivative Input and Output

APPENDIX

STATISTICAL ANALYZER SYSTEM

The Statistical Analyzer system can be used as a general purpose computer system and can also perform the following special operations:

1. Auto-Correlation
2. Cross-Correlation
3. Power Spectra (Hanned)
4. Cospectra and Quadspectra (Hanned)
5. RMS Amplitude versus Frequency
6. Transfer Function Gain and Phase
7. Coherence Function
8. Single and Joint Probability Distributions
9. Mean, Variance, Skewness, and Kurtosis
10. Statistical Confidence Tests

Functional Description (Fig. A-1)

The Statistical Analyzer system is comprised of two computational devices, a DDP-116 Honeywell computer and an Astrodata convolver; four input/output and memory devices; three Control Data 607 tape drives; a Datadisc disc memory; a Control Data 405 card reader; a Video Systems display unit; and the logic required to interface these devices.

The computer transmits instructions and data to the devices via the interface logic. When a device is ready to participate in a data transfer with the computer, the interface logic transmits a data request to the computer. In response to this request, one or more data characters are transferred between the computer and the requesting device via the interface logic.

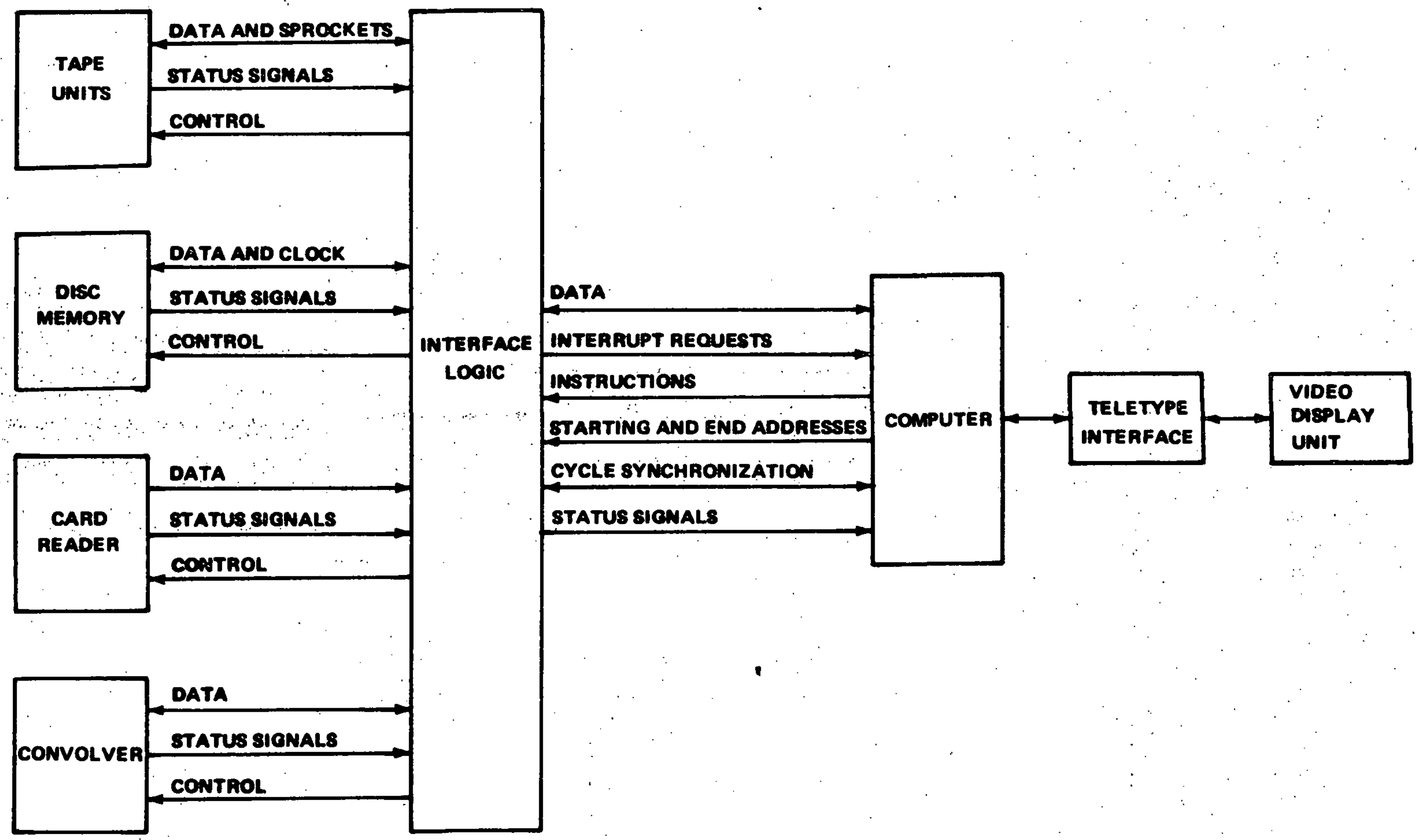


Figure A-1. Statistical Analyzer system, overall block diagram.

For each data transfer, an address in the computer memory must be specified. Blocks of addresses are specified in terms of starting and ending addresses to be associated with transfers between the computer and each of the other devices. Having received the proper addresses, the interface logic stores and processes these address data in order to specify addresses for individual transfers in consecutive order until the block of assigned addresses has been used.

The interface provides various control signals to the devices as required to implement instructions received from the computer, synchronizes data transfers, formats data as necessary, and summarizes status signals received from the devices to simplify monitoring by the computer.

The special operations performed by the system are accomplished through use of the Astrodata convolver. The convolver is an extremely high speed arithmetic device and special purpose computer with its own core memory. It can respond to the following instructions:

1. Load
2. Unload
3. Auto-Correlate
4. Cross-Correlate
5. Compute Power Spectral Density
6. Multiply and Sum

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APPROVAL

DDP-116 GENERAL DIGITAL FILTERING

By Jack A. Jones and Ronald J. Graham

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

H. HOELZER
Director, Computation Laboratory

CHARLES E. HOUSTON
Chief, Data Reduction Branch

ROY J. COCHRAN
Chief, Engineering Computation Division

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